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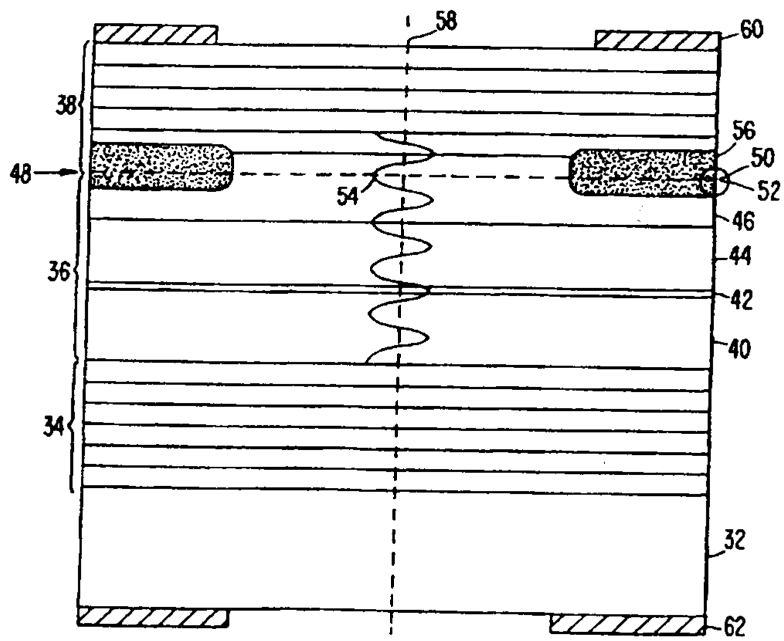
(54) Title: VERTICAL CAVITY SURFACE EMITTING LASER WITH TUNNEL JUNCTION

(57) Abstract

A vertical cavity surface emitting laser (VCSEL) includes a bottom mirror stack disposed above a semiconductor substrate, an optical cavity including an active region disposed above the bottom mirror stack, and a top mirror stack disposed above the optical cavity. A tunnel junction interface between an n-doped layer of GaAs and a p-doped layer of GaAs for converting electrons to holes is incorporated in the optical cavity or in the period of either of the mirror stacks adjacent the optical cavity. The tunnel junction interface effectively converts n carriers to p carriers, which eliminates the need for a p-type contact. As a result, the VCSEL is able to include a second n-type contact, rather than the p-type contact suggested by conventional techniques, and a thin p-doped GaAs layer. The advantages of having a second n-type contact rather than a p-type contact include a lower electrical resistance and lower optical loss for the VCSEL. When the invention is embodied in a VCSEL with an intracavity contact, one of the mirrors can be undoped. This futher reduces optical loss for the VCSEL. The VCSEL can be electrically pumped using first and second contacts to n-material portions of the VCSEL to emit coherent electromagnetic radiation having a wavelength in a range from 1250 nm to 1650 nm.



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TITLE OF THE INVENTION

VERTICAL CAVITY SURFACE EMITTING LASER WITH TUNNEL JUNCTION

FIELD OF THE INVENTION

This invention relates to vertical cavity surface emitting lasers (VCSELs), and more particularly to VCSELs having a tunnel junction interface and two n-type contacts or an intracavity contact.

BACKGROUND OF THE INVENTION

A VCSEL is a semiconductor laser consisting of a semiconductor layer of optically active material, such as gallium arsenide or indium gallium arsenide, sandwiched between highly-reflective layers of metallic material, dielectric material, epitaxially-grown semiconductor material or combinations thereof, the layers forming a mirror stack. Conventionally, one of the mirror stacks is partially reflective so as to pass a portion of the coherent light built up in the resonant optical cavity formed by the mirror stack/active layer sandwich.

Laser structures require optical confinement and carrier confinement to achieve efficient conversion of pumping electrons to stimulated photons. A semiconductor may lase if it achieves population inversion in the energy bands of the active material. The standing wave in the optical cavity has a characteristic cross-section giving rise to an electromagnetic mode. A desirable electromagnetic mode is the single fundamental mode, for example, the HE_{11} mode of a cylindrical waveguide. A single mode signal from a VCSEL is easily coupled into an optical fiber, has low divergence, and is inherently single frequency in operation.

All s miconductor las rs rely on stimulated recombination of electrons and hol s in the d pletion region of a p-n junction. As a r sult, most such lasers require l ctrical contacts to both p and n regions, to supply both holes and electrons for recombination.

Recently, an edge-emitting semiconductor laser with two n-type contacts was fabricated. This is described in A.R. Sugg, et al., "n-p-(p+-n+)-n $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum-well laser with p+-n+ GaAs-InGaAs tunnel contact on n-GaAs," *Applied Physics Letters* 62(20), 17 May 1993, pp. 2510-2512. In Sugg, et al., electrons from one of the n contacts were converted to holes through the use of a reverse-biased tunnel junction. This conversion allowed the requirement for both holes and electrons to be satisfied, while still using two n-type contacts. The purpose of the work in Sugg, et al. was to allow an "n-up" edge-emitting semiconductor laser to be fabricated on an n-type substrate.

SUMMARY OF THE INVENTION

A vertical cavity surface emitting laser (VCSEL) constructed according to the invention includes a pair of mirror stacks with an optical cavity including an active region disposed between the mirror stacks. A tunnel junction interface between an n-doped layer of GaAs and a p-doped layer of GaAs is incorporated in the optical cavity, or in one of the mirror stacks adjacent the optical cavity. The tunnel junction interface effectively converts n carriers to p carriers, which eliminates the need for a p-type contact. As a result, the p-type contact required in a conventional VCSEL, can be eliminated so that the VCSEL according to the invention can be energized using a pair of n-type contacts.

The advantages of having two n-type contacts, rather than a p-type contact and an n-type contact, are lower electrical resistance and lower optical loss. Moreover, when the inv ntion is embodi d in a VCSEL with an intracavity contact, one of the mirror stacks can be undoped. This further reduces optical loss for the VCSEL.

An annular resistive layer can be incorporated into the VCSEL for current confinement. The VCSEL can be electrically pumped to emit coherent electromagnetic radiation having a wavelength in a range from 1250 nm to 1650 nm.

Other features and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the features of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 shows a conventional VCSEL having a typical doping profile;

FIG. 2 shows an implant-constricted VCSEL having a tunnel junction interface and with current driven through both mirror stacks according to a first embodiment of the invention;

FIG. 3 shows an oxide-constricted VCSEL having a tunnel junction interface and with current driven through both mirror stacks according to a second embodiment of the invention; and

FIG. 4 shows an oxide-constricted VCSEL having a tunnel junction interface and with an intracavity contact through which current bypasses one mirror stack according to a third embodiment of the invention

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In this description, "top" or "upper" are relativ to the semiconductor substrate and refer to regions of the VCSEL that are away from the substrate, and "bottom" and "lower" are relative terms meaning toward the substrate.

Referring to FIG. 1, a conventional VCSEL having a typical doping profile includes an n-substrate 12. An n-doped mirror stack 14 is fabricated above the n-substrate. An optical cavity 16 including an active region is fabricated above the n-doped mirror stack. The optical cavity includes an n-doped layer 18 confronting the n-doped mirror stack, a quantum well region 20 confronting n-doped layer 18, and a p-doped layer 22 confronting quantum well region 20. A p-doped mirror stack 24 is disposed above optical cavity 16. A p-metal contact 26 is applied to the top surface of p-doped mirror stack 24. An n-metal contact 28 is applied to the bottom surface of the n-substrate.

A vertical cavity surface emitting laser (VCSEL) constructed on a semiconductor substrate according to the principles of the invention includes a bottom mirror stack disposed above the substrate, an optical cavity including an active region disposed above the bottom mirror stack, and a top mirror stack disposed above the optical cavity. The optical cavity including the active region presents a central vertical axis. Two metallized electrodes contact n-type material of the VCSEL. A tunnel junction interface between an n-doped layer and a p-doped layer is incorporated within the optical cavity or in the period of either mirror stack adjacent the optical cavity. The tunnel junction interface includes two layers of GaAs, one being p-doped and the other being n-doped. The tunnel junction interface is part of the same epitaxial growth as the optical cavity or the mirror stacks.

Conv ntional VCSELs have an n-type contact and a p-type contact, as shown in FIG. 1. The tunnel junction interface taught herein effectively conv rts n carriers to p carriers, which eliminates the need for a p-type contact. As a result, the VCSEL is able to include a second n-type contact, rather than the p-type contact suggested by conventional techniques, and a thin p-doped GaAs layer.

The advantages of having a second n-type contact, as taught herein, rather than a p-type contact include a lower electrical resistance and lower optical loss for the VCSEL. Moreover, when the invention is embodied in a VCSEL with an intracavity contact, one of the mirror stacks can be undoped. This further reduces optical loss in the VCSEL.

Such VCSEL has lower electrical resistance than the conventional VCSEL structure shown in FIG. 1 because ohmic contacts to n-type material have lower resistance than contacts to p-type material. Conduction through an n-type mirror stack is better than conduction through a p-type mirror stack, and the absence of p-type dopants in such conducting mirror stack reduces optical loss.

In a first embodiment of the invention as shown in FIG. 2, a VCSEL is implant-constricted for current confinement. Two metallized contacts of n-type material are used in the VCSEL. The optical cavity includes a tunnel junction interface to convert electrons into holes. Referring to FIG. 2, such an implant-constricted VCSEL includes on a GaAs substrate 32 a bottom n-type mirror stack 34 disposed above the substrate, an optical cavity 36 including an active region and disposed above the bottom mirror stack, and a top n-type mirror stack 38 disposed above the optical cavity. The bottom and top n-type mirror stacks ar both fabricated from a system selected from (a) alternating layers of

GaAs and AlAs, or (b) alternating layers of GaAs and AlGaAs. Both bottom n-type mirror stack 34 and top n-type mirror stack 38 are doped at less than 5 x $10^{18}/cm^3$. Optical cavity 36 preferably includes InGaAsP and is wafer fused to bottom n-type mirror stack 34.

The InGaAsP optical cavity includes an n-cladding layer 40 (consisting of InGaAsP and InP) disposed above bottom mirror stack 34, quantum wells 42 above the n-cladding layer, and a p-cladding layer 44 (consisting of InGaAsP and InP) disposed above the quantum wells. A GaAs layer 46, which is p-doped at 5 x $10^{17}/cm^3$, is fabricated above the p-cladding layer 44 to aid conversion of n carriers to p carriers. A tunnel junction interface 48 is formed above p-doped GaAs layer 46. The tunnel junction interface has two confronting layers of epitaxially grown GaAs: a first .02 mm layer 50, which is n+ doped at greater than 1 x $10^{19}/cm^3$, in confronting relationship with a second .02 mm layer 52 which is p+ doped at greater than 1 x $10^{19}/cm^3$. Tunnel junction interface 48 is positioned at a minimum of the standing wave optical intensity profile 54 shown in FIG. 2.

Alternatively, the tunnel junction interface can be formed in the mirror period of either mirror stack that is adjacent the optical cavity

The top n-type mirror stack 38 is wafer fused to the InGaAsP optical cavity 36. Protons (H+) are implanted along an annular section 56 of top n-type mirror stack 38 at tunnel junction interface 48 The annular section is radially displaced from and centered about the central vertical axis 58 of the optical cavity. Annular implant section 56 has a higher electrical resistivity than other parts of top n-type mirror stack 38 and constricts current flow to within the annular section.

A first n-metal contact 60 is applied to the n-type mirror stack 38. A second n-m tal contact 62 is applied to substrat 32. Electrical current can be driven through both the top mirror stack and the bottom mirror stack with first and second electrodes 60, 62, which contact n-type material of the VCSEL.

The VCSEL shown in FIG. 2 is electrically powered to emit coherent electromagnetic radiation having a wavelength in a range from 1250 nm to 1650 nm.

In a second embodiment of the invention as shown in FIG. 3, a VCSEL is oxide-constricted for current confinement. Two n-metal electrodes contact n-type material of the VCSEL. A tunnel junction interface is incorporated into the VCSEL to convert electrons to holes. The two layers of the tunnel junction interface are composed of epitaxially-grown GaAs, one being p-doped and the other being n-doped. The tunnel junction interface effectively converts n carriers to p carriers, which eliminates the need for a p-type contact. As a result, the VCSEL is able to include a second n-type contact, rather than the p-type contact suggested by conventional techniques. The advantages of having a second n-type contact rather than a p-type contact include a lower electrical resistance and lower optical loss for the VCSEL.

Referring to FIG. 3, such a VCSEL includes on a semiconductor substrate 66 a bottom n-type mirror stack 67 formed above the substrate, an optical cavity 68 including an active region presenting a central vertical axis 70 and disposed above the bottom mirror stack, and a top n-type mirror stack 72 disposed above optical cavity 68. The top n-type mirror stack 72 and the bottom n-type mirror stack 67 are each fabricated from a system of (a) alternating layers of GaAs and AlGaAs, or (b) alternating layers of GaAs and AlAs. Both the bottom n-type mirror stack and the top n-type mirror stack have

less than 5 x $10^{18}/cm^3$ doping. Optical cavity 68 preferably includes InGaAsP. Top n-type mirror stack 72 and bottom n-type mirror stack 67 are ach wafer fus d to optical cavity 68.

The InGaAsP optical cavity 68 includes an n-cladding layer 74 (consisting of InGaAsP and InP), quantum wells 76 above the n-cladding layer, and a p-cladding layer 78 (consisting of InGaAsP and InP) disposed above the quantum wells. A GaAs layer 80, which is p-doped at 5 x $10^{17}/cm^3$, is fabricated above p-cladding layer 78 to aid conversion of n carriers to p carriers. A tunnel junction interface 82 includes two epitaxially-grown layers of GaAs in confronting relationship. One layer 84 is a .02 mm layer, which is n+ doped at greater than 1 x $10^{19}/cm^3$. The other layer 86 is a .02 mm layer, which is p+ doped at greater than 1 x $10^{19}/cm^3$. Tunnel junction interface 82 is positioned at a minimum of the standing wave optical intensity profile 88.

A thin AlGaAs oxidation layer 90 is formed as an annular-shaped section in the optical cavity. The annular-shaped section is radially-displaced from and centered about central vertical axis 70. This thin AlGaAs oxidation layer has a higher electrical resistivity than p-doped GaAs layer 80 and constricts current to move through annular section 90.

A first metal contact 92 is applied to top n-type mirror stack 72 and a second metal contact 94 is applied to n-type GaAs substrate 66. Current is driven through both the top and bottom mirror stacks using first and second metal contacts 92, 94. The VCSEL shown in FIG. 3 preferably emits coherent electromagnetic radiation at a wavelength in a range from 1250 nm to 1650 nm.

Alternatively, the tunnel junction interface can be located in a mirror period adjacent the optical cavity in either the top or bottom mirror stacks.

In the third mbodim nt of th invention, a VCSEL incorporates a tunnel junction interface and two n-type contacts to n-mat rial in the VCSEL. According to an aspect of the invention, one of the n-type contacts is made to n-type material within the optical cavity. Current bypasses one of the bottom or top mirror stacks through this intracavity contact. Thus, one of the mirror stacks can be undoped.

Referring to FIG. 4, such a VCSEL includes on an n-GaAs semiconductor substrate 98 a bottom n-type mirror stack 100 fabricated above the n-GaAs substrate. An optical cavity 102 including an active region is disposed above bottom n-type mirror stack 100 and presents a central vertical axis 103. An undoped top mirror stack 104 is fabricated above optical cavity 102.

Optical cavity 102 includes an n-cladding layer 106 of InGaAsP, doped at $2 \times 10^{18}/cm^3$. A quantum well region 108 is formed beneath n-cladding layer 106. A p-cladding layer 110 of InGaAsP, doped at $3 \times 10^{17}/cm^3$, is disposed beneath quantum well region 108.

A layer 112 of GaAs, which is p-doped at $5 \times 10^{17}/cm^3$, is disposed in confronting relationship beneath p-cladding layer 110 to aid conversion of n carriers to p carriers. A thin oxidation layer 114 such as AlGaAs, shaped in the form of an annulus, is disposed beneath and in confronting relationship with p-doped layer 112. Annular oxidation layer 114 is radially-displaced from and centered about central vertical axis 103. The thin annular oxidation layer has a higher electrical resistance than other parts of the optical cavity. Annular-shaped oxidation layer 114 confines current through the annulus in the optical cavity. Current confinement can also be accomplished in this embodiment by proton implantation.

A tunnel junction interface 116 b tween two confronting epitaxially-grown layers of GaAs is disposed in th optical cavity beneath annular oxidation lay r 114. The two confronting layers are a first .02 mm layer 118, which is p-doped greater than 1 x $10^{19}/cm^3$, and a second .02 mm layer 120, which is n-doped greater than 1 x $10^{19}/cm^3$. Tunnel junction interface 116 confronts n-type bottom mirror stack 100. A reverse conducting tunnel junction requires high p and n doping levels for a short distance. This has the potential to introduce loss. This loss is largely avoided by placing tunnel junction interface 116 at a minimum in the standing wave of the optical cavity.

A first n-metal electrode 122 bypasses the bottom and top mirror stacks and makes contact with n-cladding layer 106 in optical cavity 102. The VCSEL shown in FIG. 4 can be electrically pumped using first and second metal contacts 122, 124 to emit coherent electromagnetic radiation having a wavelength in a range from 1250 nm to 1650 nm.

A VCSEL constructed according to the principles of the invention has a lower electrical resistance than a conventional VCSEL because ohmic contacts to n-type material have lower resistance than contacts to p-type material. Conduction through an n-type mirror stack is better than conduction through a p-type mirror stack, and the absence of p-type dopants in the n-type mirror stack reduces optical loss.

Thus, using a tunnel junction interface with two n-type mirror stacks, as taught herein, reduces optical loss as compared to a conventional VCSEL having a p-type mirror and an n-type mirror. Additionally, as compared to a conventional VCSEL with a p-type mirror and an n-type mirror, using a tunnel junction and an intracavity contact with one n-type mirror also reduces optical loss according to th invention because the other mirror can be undoped.

While sev ral particular forms of the invention have been illustrated and described, it will also be apparent that various modifications can be made without departing from th spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A vertical cavity surface mitting laser (VCSEL) comprising:

a pair of mirror stacks;

an optical cavity including an active region disposed between said mirror stacks;

a tunnel junction interface between an n-doped layer and a p-doped layer located in the VCSEL for converting electrons into holes; and

a pair of n-material contacts causing current flow through said active region in said optical cavity.

2. The VCSEL of claim 1, wherein:

said tunnel junction interface is located within said optical cavity.

3. The VCSEL of claim 1, wherein:

said tunnel junction interface is located within a period of one of said mirror stacks adjacent said optical cavity.

4. The VCSEL of claim 1, wherein:

both of said mirror stacks are n-type semiconductor mirror stacks.

5. The VCSEL of claim 1, wherein:

electrical current is driven through both of said mirror stacks.

6. The VCSEL of claim 1, wherein:

said contacts are located so that current flow bypasses a portion of one of said mirror stacks.

7. The VCSEL of claim 1, wherein:

at least one of said mirror stacks is undoped.

8. The VCSEL of claim 1, wherein:

said optical cavity includes InGaAsP; and

said mirror stacks are wafer fused to said optical cavity and include alternating layers of GaAs and AlGaAs.

9. The VCSEL of claim 1, wherein:

the VCSEL emits coherent electromagnetic radiation having a wavelength in a range from 1250 nm to 1650 nm.

10. The VCSEL of claim 1, wherein:

the tunnel junction interface is positioned to be at a minimum of the standing wave in the optical cavity.

11. The VCSEL of claim 1, further comprising:

an annular resistive layer for current confinement.

12. The VCSEL of claim 11, wherein:

said annular resistive layer is a proton implantation layer.

13. The VCSEL of claim 11, wherein:

said annular resistive layer is an oxidation layer including AlGaAs.

14. Th VCSEL of claim 1, wher in:

said mirror stacks are each fabricated from material s lected from the group consisting of metallic, di lectric, epitaxially grown semiconductor, and combinations thereof.

15. A method of constructing a vertical cavity surface emitting laser (VCSEL) on a semiconductor substrate comprising the following steps:

(A) disposing a bottom mirror stack above the substrate;

(B) disposing an optical cavity including an active region above the bottom mirror stack;

(C) disposing a top mirror stack above the optical cavity;

(D) forming a tunnel junction interface between an n-doped layer and a p-doped layer for converting electrons to holes; and

(E) applying a pair of n-material contacts to provide current flow through the active region in the constructed VCSEL.

16. The method of claim 15, further comprising the step:

locating the tunnel junction interface within the optical cavity.

17. The method of claim 15, further comprising the step:

locating the tunnel junction interface within a period of either mirror stack adjacent the optical cavity.

18. The method of claim 15, wherein:

the n-material portion is in the top mirror stack.

19. The method of claim 15, wherein:
the n-material portion is in the optical cavity.

20. The method of claim 15, wherein:
the top mirror stack is undoped.

21. The method of claim 15, wherein:
the optical cavity includes InGaAsP.

22. The method of claim 15, further comprising the step:
wafer fusing one of the mirror stacks to the optical cavity.

23. The method of claim 15, further comprising the step:
wafer fusing both mirror stacks to the optical cavity.

24. The method of claim 15, further comprising the step:
positioning the tunnel junction interface to be at a minimum of the standing wave in the optical cavity.

25. The method of claim 15, wherein
the tunnel junction interface includes an n-doped layer of GaAs in confronting relationship with a p-doped layer of GaAs

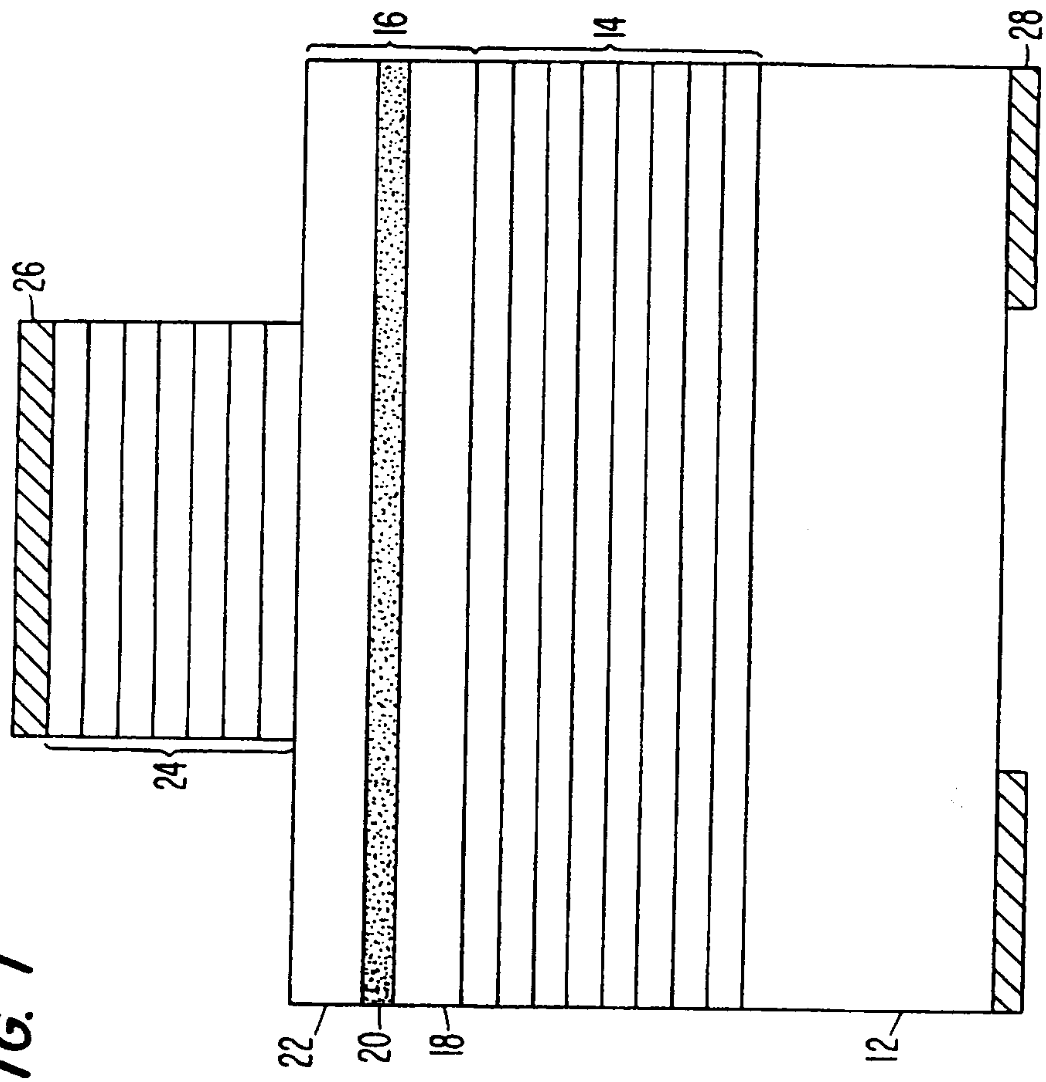
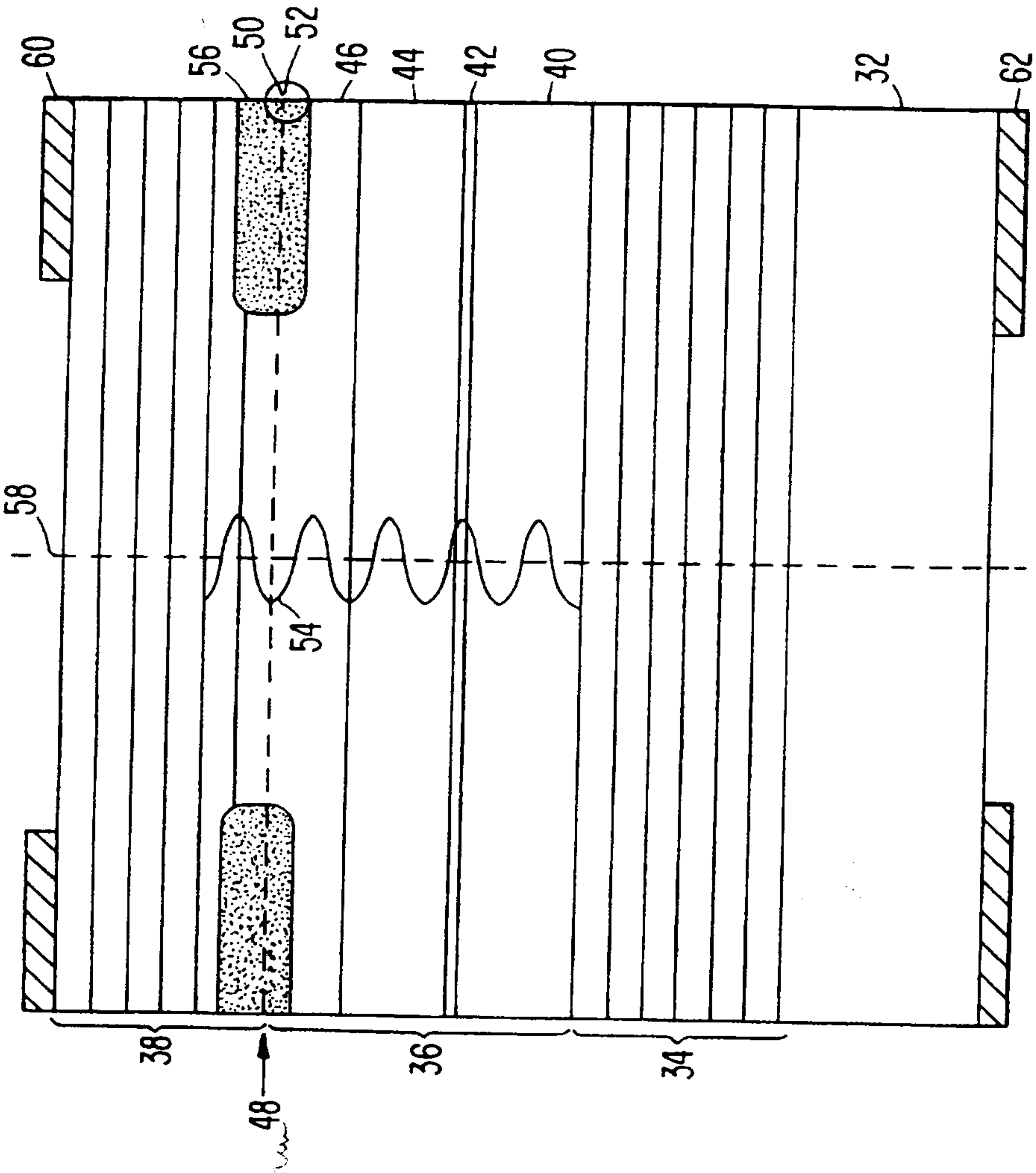


FIG. 1

FIG. 2



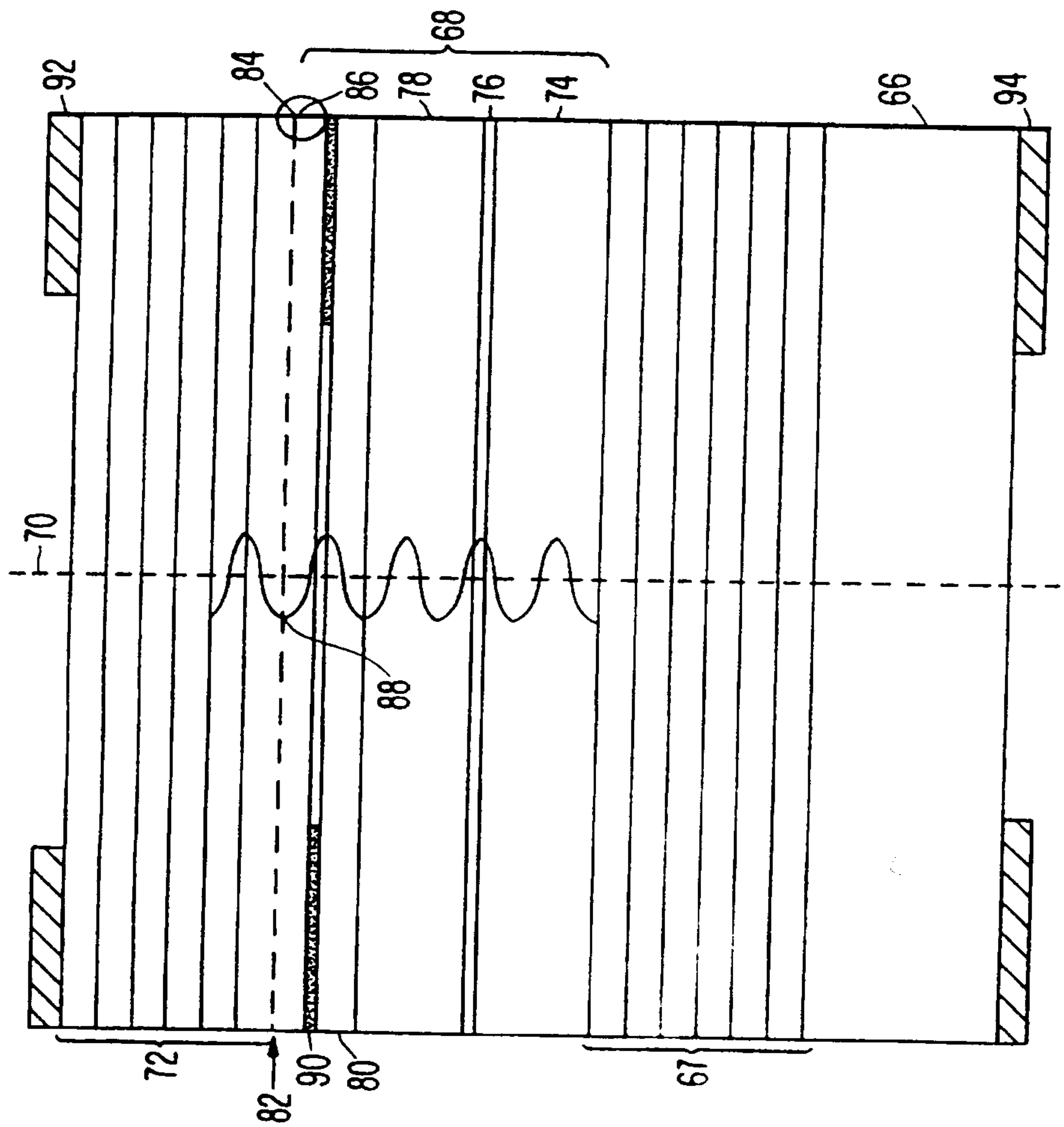


FIG. 3

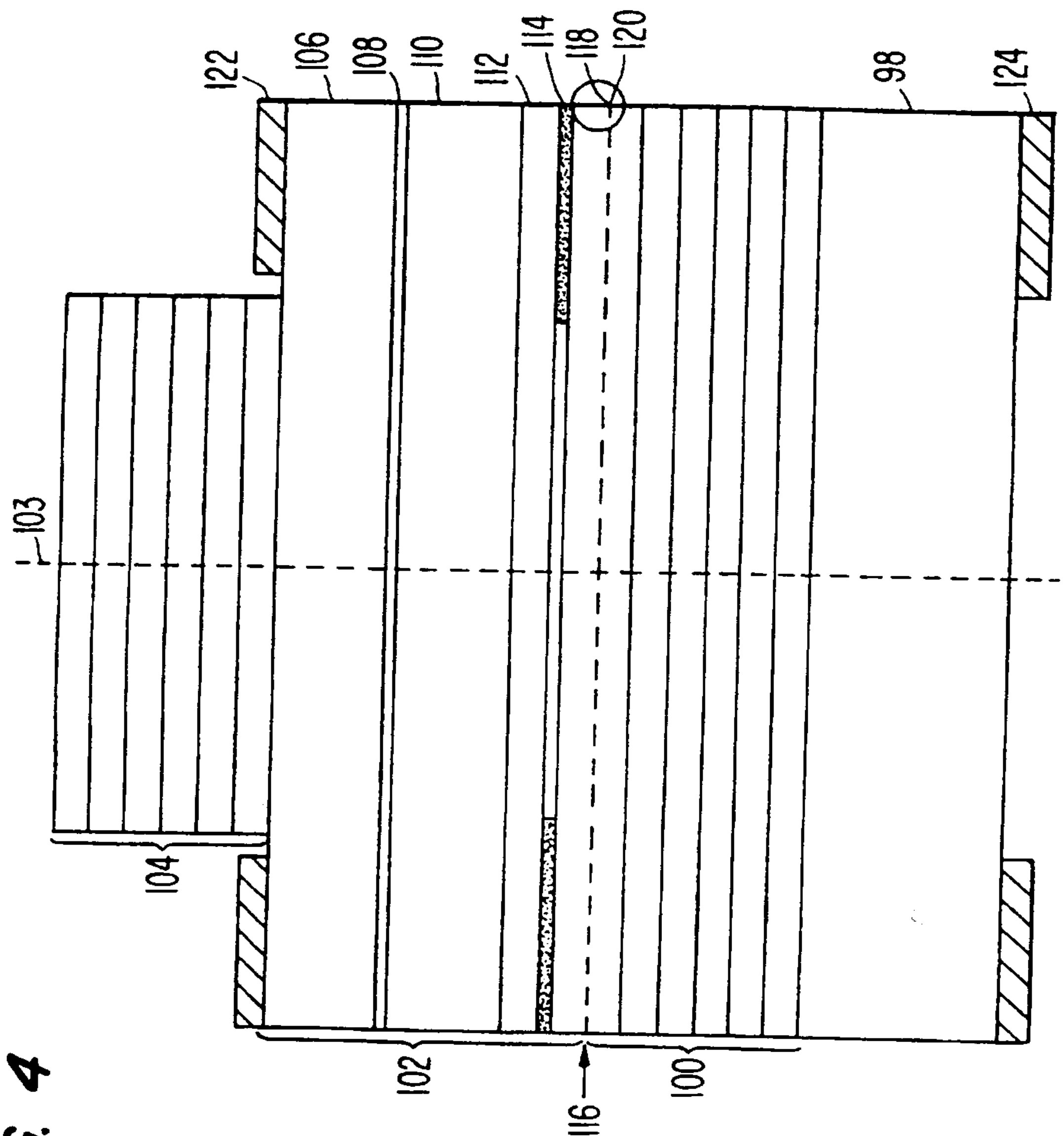


FIG. 4

INTERNATIONAL SEARCH REPORT

Inte ional Application No
PCT/US 97/12147

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/085

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 709 939 A (HEWLETT PACKARD CO) 1 May 1996	1,5,11, 12,14, 15,25
A	see column 3, line 46 - column 7, line 37; figures 2A,3A ---	6
A	SUGG A R ET AL: "N-P-(P+-N+)-N ALYGA1-YAS-GAAS-INXGA1-XAS QUANTUM-WELL LASER WITH P+-N+ GAAS-INGAAS TUNNEL CONTACT ON N-GAAS" APPLIED PHYSICS LETTERS, vol. 62, no. 20, 17 May 1993, pages 2510-2512, XP000303799 cited in the application see the whole document --- -/--	1,15

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
24 October 1997	30/10/1997

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WIPIEJEWSKI T ET AL: "CHARACTERIZATION OF TWO-SIDED OUTPUT VERTICAL-CAVITY LASER DIODES BY EXTERNAL OPTICAL FEEDBACK MODULATION" PROCEEDINGS OF THE LASERS AND ELECTRO-OPTICS SOCIETY ANNUAL MEETING (LEOS), SAN JOSE, NOV. 15 - 18, 1993 CO-LOCATED WITH OPTCON '93, no. -, 15 November 1993, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, page 564/565 XP000467154 see figure 1 ---	1,6
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A	CHUA C L ET AL: "LONG WAVELENGTH VCSELS USING ALAS/GAAS MIRRORS AND STRAIN-COMPENSATED QUANTUM WELLS" PROCEEDINGS OF THE IEEE/CORNELL CONFERENCE ON ADVANCED CONCEPTS IN HIGH SPEED SEMICONDUCTOR DEVICES AND CIRCUITS, ITHACA, NEW YORK, AUG. 7 - 9, 1995, 7 August 1995, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, pages 361-363, XP000626624 see the whole document ---	1,4,6-8, 15, 18-20,22
A	THIBEAULT B J ET AL: "REDUCED OPTICAL SCATTERING LOSS IN VERTICAL-CAVITY LASERS USING A THIN (300 A) OXIDE APERTURE" IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 8, no. 5, 1 May 1996, pages 593-595, XP000589250 see page 593, right-hand column, paragraph II; figure 1 -----	1,7,15, 20

INTERNATIONAL SEARCH REPORT

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